An eddy permitting global ocean and sea-ice model on a quasi-uniform cube-sphere grid suitable for decadal timescale data assimilation

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- http://mitgcm.org
- http://www.ecco-group.org
- http://ecco.jpl.nasa.gov/cube_sphere

Introduction

Introduction:

Ocean state estimation (or reanalysis) is now possible globally for decadal time windows.

For example, the Estimating the Circulation and Climate of the Ocean (ECCO) project has demonstrated the feasibility of routine decadal time-scale ocean data assimilation at modest resolution.

The ECCO reanalyses provide a planetary scale, time varying "brain-scan" of the state of the ocean.
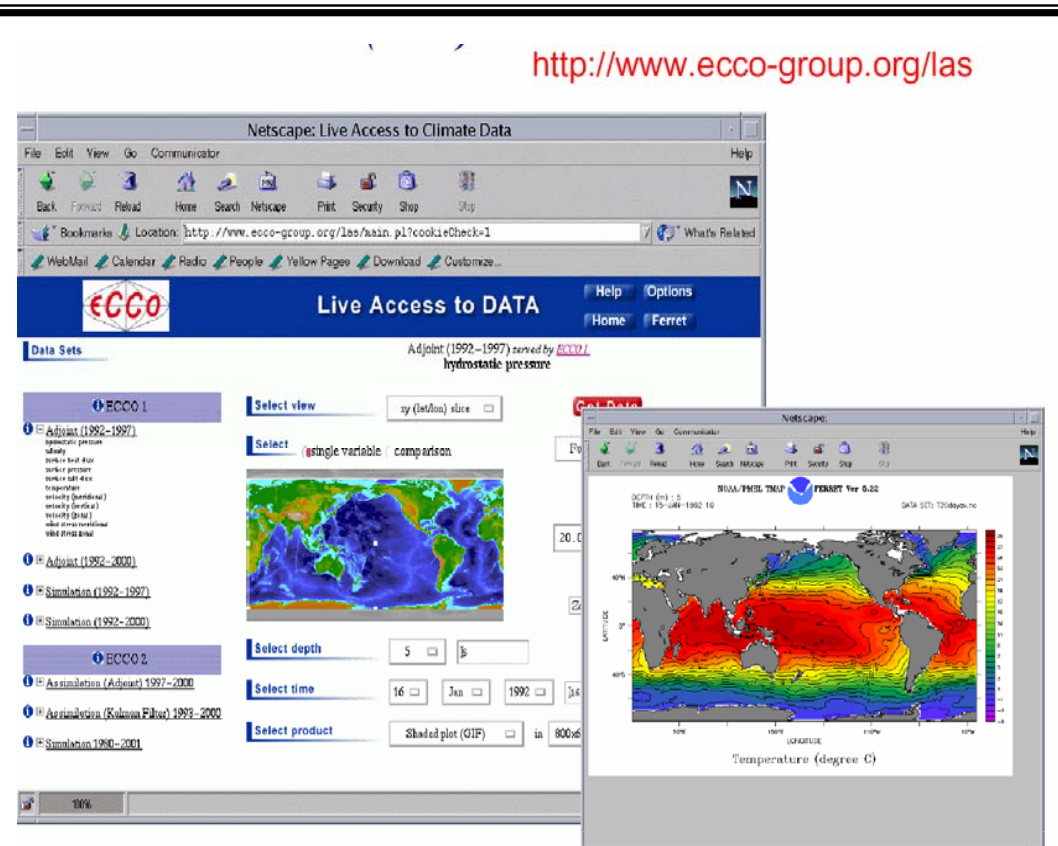
The ECCO consortium (MIT, Scripps, JPL) uses the M.I.T. General Circulation Model (MITgcm) together with satellite and in-situ observations to produce ocean state-estimates.

ECCO state estimates for 1992-2002 are available online

This talk:

Reports on key innovations in an MITgcm configuration that resolves turbulent mesoscale eddies, sharp boundary currents, that includes polar oceans (and associated sea-ice).

These innovations make the configuration computationally viable for state estimation.

This configuration is being constructed as the basis for an oceanic reanalysis that will explicitly monitor
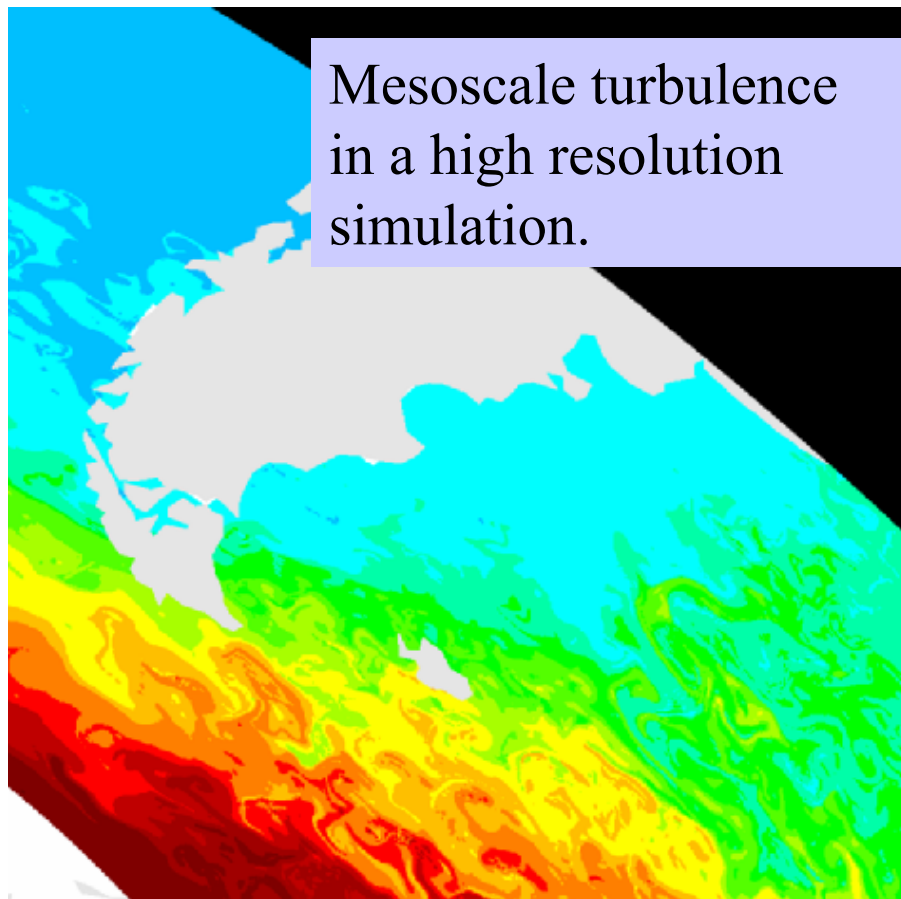
eddy fluxes

meandering of fronts

tropical instabilities

sea-ice dynamics

……

Mesoscale turbulence in a high resolution simulation.

Ocean circulation contains significant energy at resolutions of ~10km. Current generation state estimation systems do not resolve the turbulent mesoscale eddies.

Challenges:

State estimation is computationally vastly more demanding than prognostic simulation. It generally involves iterating to minimize a cost function, J.

Each iteration involves evaluating a prognostic model integration.

We require a throughput of ~10 years/day.

➔ efficient discrete numerics

➔ scalable, parallel implementation

$$J = \frac{1}{2}\left[\left(\overline{\eta} - \overline{\eta}_{tp}\right)^T \mathbf{W}_{geoid}\left(\overline{\eta} - \overline{\eta}_{tp}\right)\right.$$

$$+ \left(\eta' - \eta'_{tp}\right)^T \mathbf{W}_{\eta_{tp}}\left(\eta' - \eta'_{tp}\right) + \left(\eta' - \eta'_{ers}\right)^T \mathbf{W}_{\eta_{ers}}\left(\eta' - \eta'_{ers}\right)$$

$$+ \left(\delta\tau_x\right)^T \mathbf{W}_{\tau_x}\left(\delta\tau_x\right) + \left(\delta\tau_y\right)^T \mathbf{W}_{\tau_y}\left(\delta\tau_y\right)$$

$$+ \left(\delta\mathbf{H}_Q\right)^T \mathbf{W}_{H_Q}\left(\delta\mathbf{H}_Q\right) + \left(\delta\mathbf{H}_F\right)^T \mathbf{W}_{H_F}\left(\delta\mathbf{H}_F\right)$$

$$+ \left(\delta\mathbf{T}_0\right)^T \mathbf{W}_T\left(\delta\mathbf{T}_0\right) + \left(\delta\mathbf{S}_0\right)^T \mathbf{W}_S\left(\delta\mathbf{S}_0\right)$$

$$+ \sum_i \left(\overline{\theta}_{1i} - \overline{\theta}_{iSST}\right)^T \mathbf{W}_{SST}\left(\overline{\theta}_{1i} - \overline{\theta}_{SSTi}\right)$$

$$+ \sum_i \left(\overline{\theta}_i - \overline{\theta}_{Levi}\right)^T \mathbf{W}_T\left(\overline{\theta}_i - \overline{\theta}_{Levi}\right)$$

$$+ \sum_i \left(\overline{\mathbf{S}}_i - \overline{\mathbf{S}}_{Levi}\right)^T \mathbf{W}_S\left(\overline{\mathbf{S}}_i - \overline{\mathbf{S}}_{Levi}\right)\right].$$

The ECCO cost function includes altimeter measurements, time varying heat-flux anomalies, insitu hydrography data.

The current generation ECCO optimizations fit to a cost function that contains 10^9 elements by optimizing a control vector with 10^9 elements.

Key Innovations

Converging meridians of conventional latitude longitude grids results in poor scaling with increasing resolution. This severely restricts timestep.

The cube-sphere grid (a conformal mapping of a cube onto the surface of a sphere) has a more isotropic grid spacing.

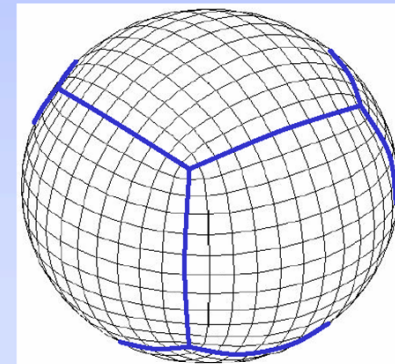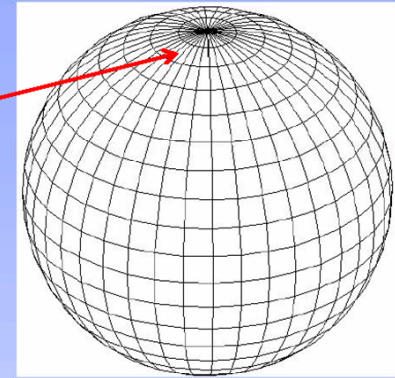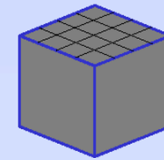## Gridding the sphere

Latitude-longitude grid
– converging meridians
– prohibitive scaling

$$\Delta x_{min} \sim N^{-2}$$

Expanded spherical cube
– near uniform resolution
– much improved scaling

$$\Delta x_{min} \sim N^{-4/3}$$

We use a 510x510 cube face. This yields a grid with mean resolution of 16km. The grid covers the globe completely. Maximum cell spacing is ~23km, minimum is ~3km.

   (In comparison a ¼ °, aspect ratio preserving lat-lon grid 80S-80N has same number of cells, but does not include polar ocean and has more severe CFL restrictions.)

Cube sphere numerics:

To handle degenerate points at a cube corner (there are 8 of these) we take advantage of the discretized vector invariant (VI) momentum equations on a C-grid.

In our VI discretization relative vorticity is derived using circulation. The discrete equations for circulation are not degenerate.
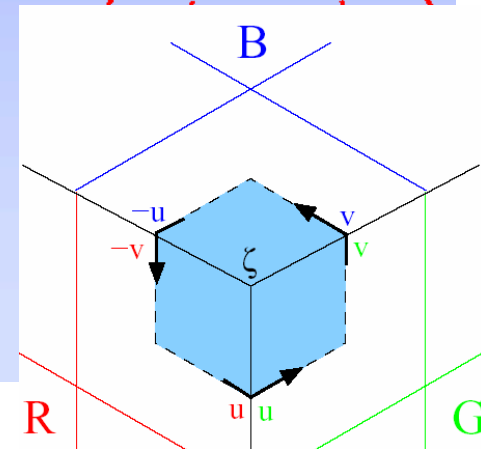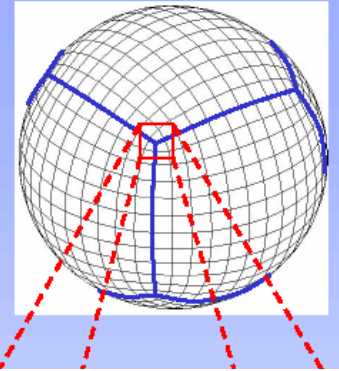
Gridding the sphere

Corners ⇒ 8 singularities
- handled cleanly by *finite volume* interpretation of model variables

Same techniques allow unstructured tiling
- Curvilinear grids (+ boundary fitting)
- Arbitrary tiling of a sphere

The vorticity everywhere is discretized as the circulation divided by the area. At the tile corners the line integral involves six segments (three pairs of values) that uniquely defines the vorticity even though the coordinate singularity is enclosed within the area.

Innovation 2 - Attaining efficient parallelism:

Rotation and permutation ops "embedded" in communication.

Several hundred CPU parallelism is achieved through domain decomposition

Communication between sub-domains applies necessary rotations. Internal numerics is "unaware" of the cube-face topology.
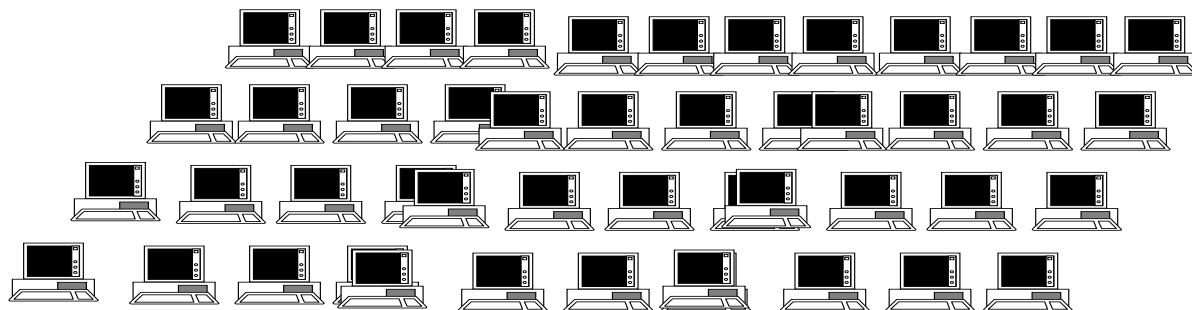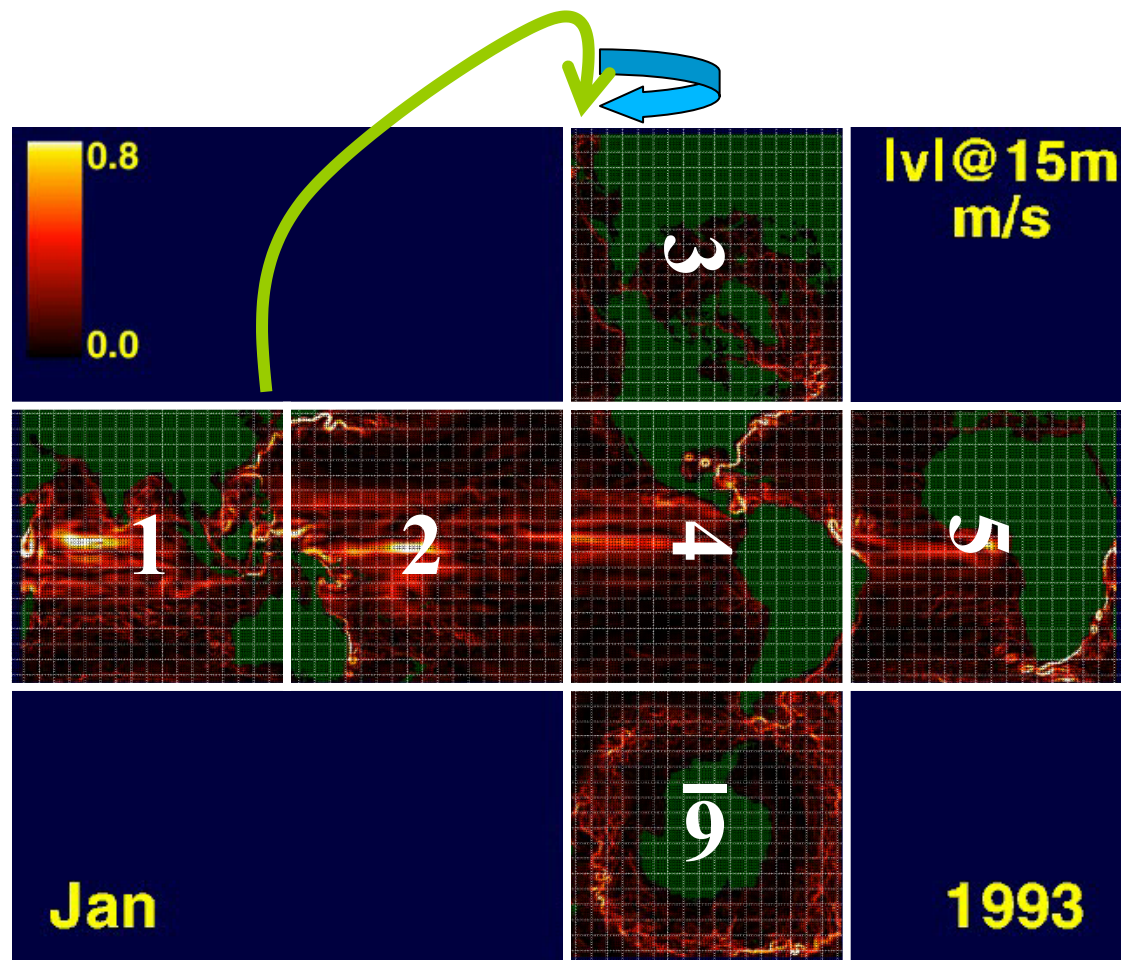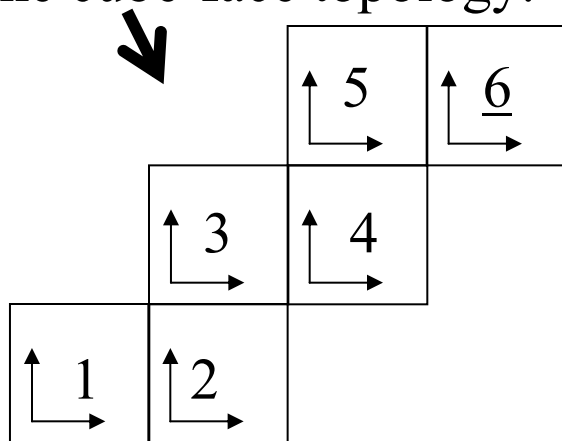
Toplogy aware communication:

Domain decomposition communications also map (u,v) on one face to (u,v) on another face.

e.g. face 1 ➔ face 5 (u,v) ➔ (v,-u)

Topology held in communication layer as a directed graph with decomposition "tile" index ranges as vertices (V) and permutation and offsets on edges (E)   – e.g.

Graph edges are precomputed for nearest neighbors.

Continuous paths around cube object.
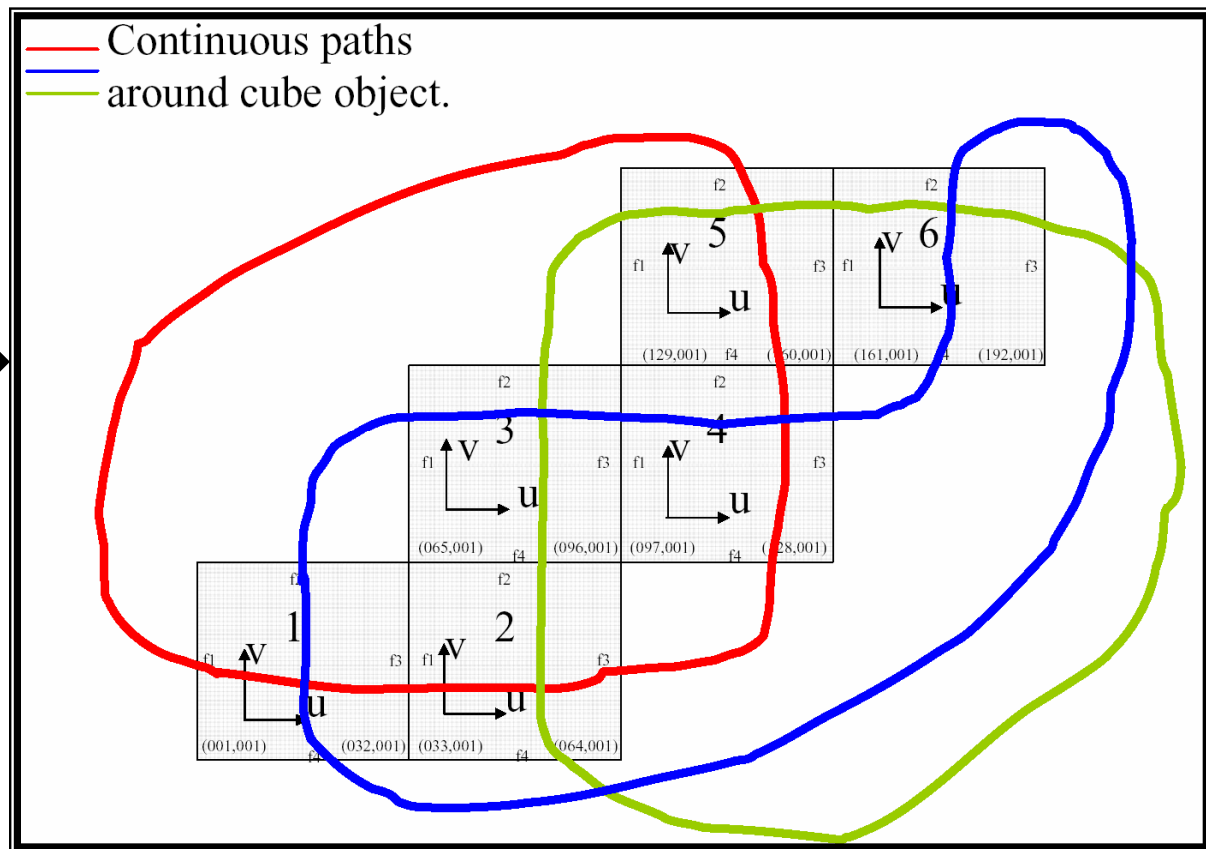
$V1 = (1{:}32,1{:}32)$
$V5 = (1{:}32,1{:}32)$
$E15 = ((0,-1),(1,0),33,-32)$

This expresses the mapping $(u,v) ➔ (v,-u)$ and the associated reindexing.

Extract from the graph for a grid with only one sub-domain per cube face and cube face sizes of 32x32.

First results

Results:

Six ~decade long scenarios have been completed.

With optimal viscosities we achieve plausible eddy variability in the ACC, the Agulhas current, the Kuroshio and the Gulf Stream.
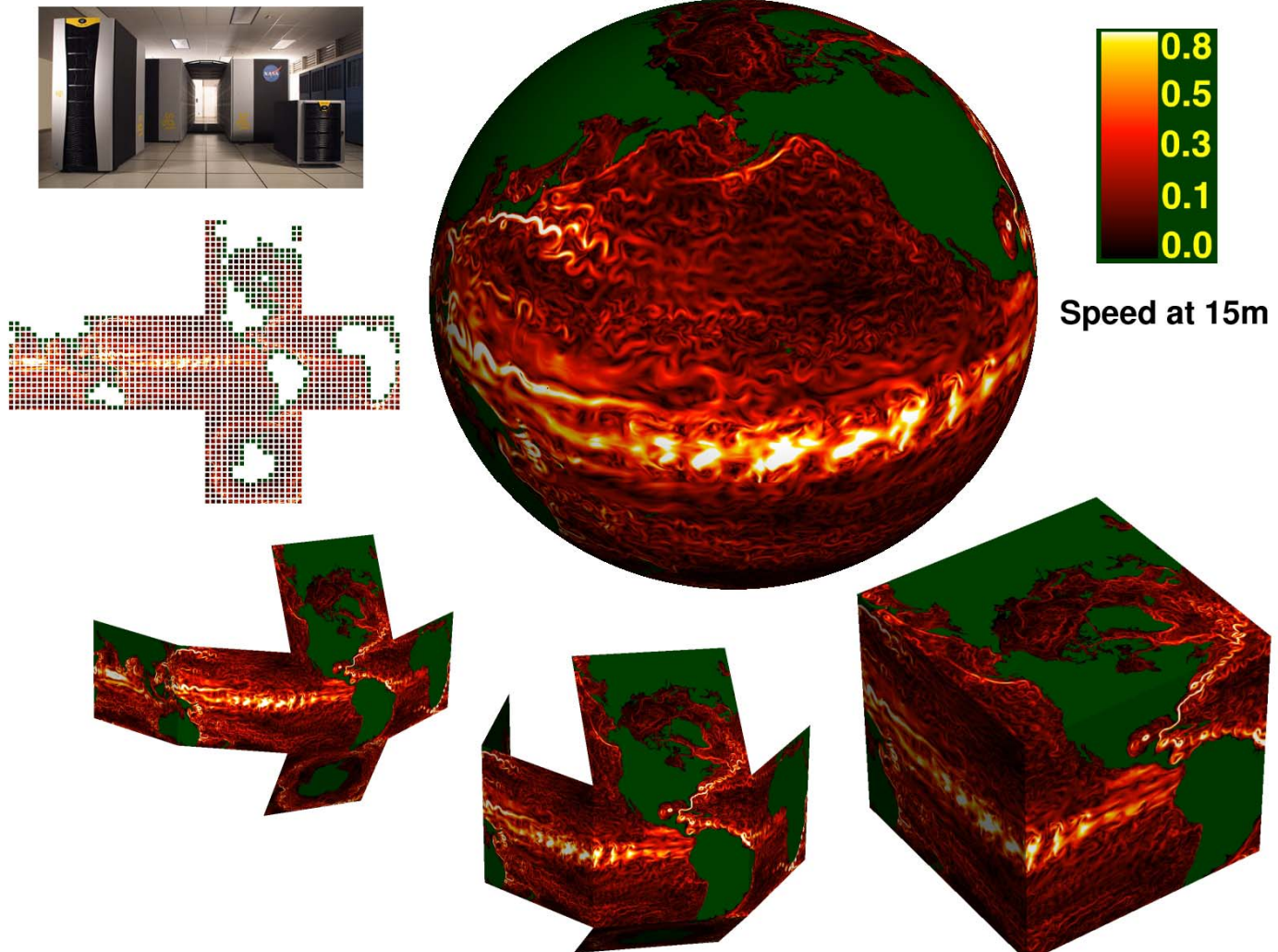
Each simulation produces ~5TB of output!

Speed at 15m

Figure shows color scale plot of speed at 15m depth. Two hundred+ processor simulation using NASA AMES SGI Altix.

Results:

Arctic and Antarctic sea-ice are well captured. Eight layer thermodynamics, Hibler rheology for dynamics.

The extent of sea-ice cover agrees well with measurements from SSM/I satellite observations.

26-Aug-1995

17-Mar-1995
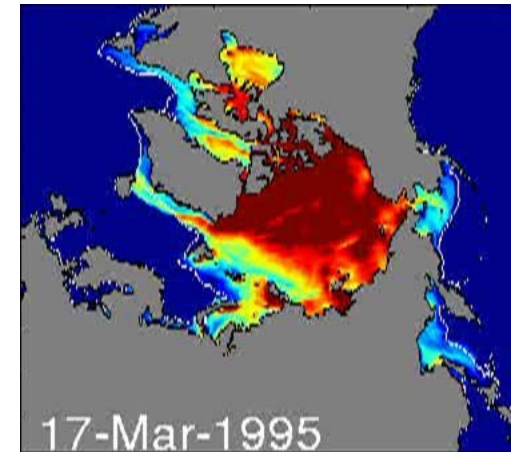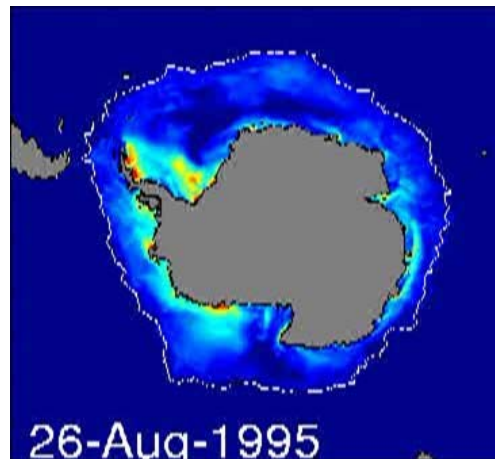
Figures show sea-ice "effective ice thickness" (ice-thickness times concentration) in the Arctic and Antarctic.

The white line shows the sea-ice edge from SSM/I satellite observations.

Conclusions:

Combining innovative numerics and sophisticated parallelism we can build a system that is powerful enough for eddy permitting global state-estimation.

Using 500 CPU SGI Altix at NASA AMES current best perfomance is 6.9 years/day → 10 years/day is within reach.

Speed with MODIS land composite image projected onto continents.
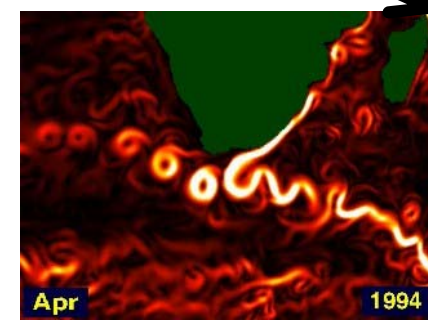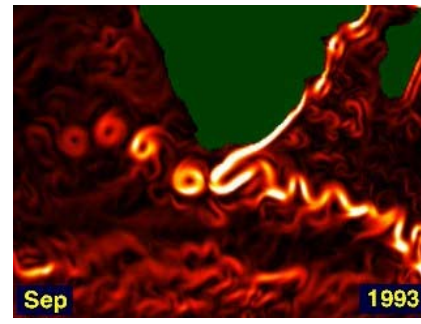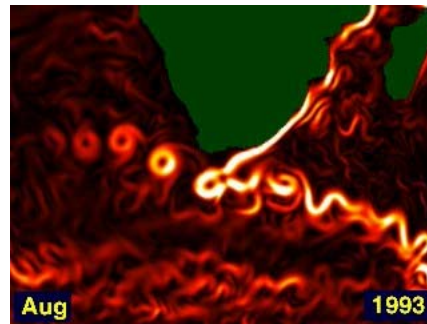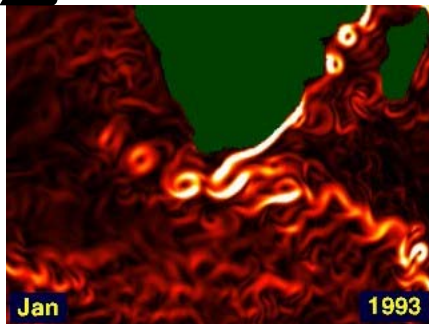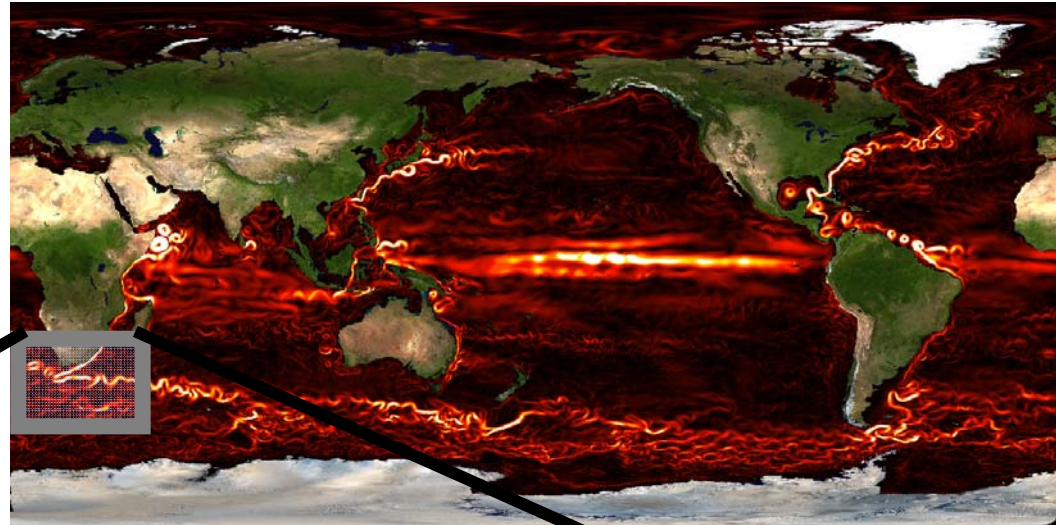
Agulhas rings zoom in.

Questions?